Sea level budget over 2003-2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo

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Abstract

From the IPCC 4th Assessment Report published in 2007, ocean thermal expansion contributed by ~50% to the 3.1 mm/yr observed global mean sea level rise during the 1993-2003 decade, the remaining rate of rise being essentially explained by shrinking of land ice. Recently published results suggest that since about 2003, ocean thermal expansion change, based on the newly deployed Argo system, is showing a plateau while sea level is still rising, although at a reduced rate (~ 2.5 mm/yr). Using space gravimetry observations from GRACE, we show that recent years sea level rise can be mostly explained by an increase of the mass of the oceans. Estimating GRACE-based ice sheet mass balance and using published estimates for glaciers melting, we further show that ocean mass increase since 2003 results by about half from an enhanced contribution of the polar ice sheets -compared to the previous decade- and half from mountain glaciers melting. Taking also into account the small GRACE-based contribution from continental waters (<0.2 mm/yr), we find a total ocean mass contribution of ~2 mm/yr over 2003-2008. Such a value represents ~80% of the altimetry-based rate of sea level rise over that period. We next estimate the steric sea level (i.e., ocean thermal expansion plus salinity effects) contribution from: (1) the difference between altimetry-based sea level and ocean mass change and (2) Argo data. Inferred steric sea level rate from (1) (~ 0.3 mm/yr over 2003-2008) agrees well with the Argo-based value also estimated here (0.37 mm/yr over 2004-2008). Furthermore, the sea level budget approach presented in this study allows us to constrain independent estimates of the Glacial Isostatic Adjustment (GIA) correction applied to GRACE-based ocean and ice sheet mass changes, as well as of glaciers melting. Values for the GIA correction and glacier contribution needed to close the sea level budget and explain GRACE-based mass estimates over the recent years agree well with totally independent determinations.

1. Introduction

While global mean ocean heat content (hence thermal expansion) rose regularly since at least the early 1990s as evidenced from in situ ocean temperature data (Antonov et al., 2005; Levitus et al., 2005; Ishii et al., 2005; Guinehut et al., 2004; Willis et al., 2004), new in situ hydrographic observations from the recently deployed Argo system (Roemmich and Owens, 2000) indicate that ocean heat content had a break since 2003 (Willis et al., 2008). If real, this means that, during the last 5 years, ocean thermal expansion has not contributed to sea level rise, unlike during the previous 10-year period where about 50% of the rate of sea level rise could be attributed to ocean thermal expansion (Bindoff et al., 2007). Yet, satellite altimetry observations indicate that global mean sea level has continued to rise since 2003, at a slightly reduced rate however (of 2.5 +/- 0.4 mm/yr over 2003-2008, Glacial Isostatic Adjustment -GIA- correction of 0.3 mm/yr applied) compared to the previous decade [see Ablain et al., 2008 for details on the satellite altimetry-based sea level data processing and errors assessment]. As shown in the IPCC 4th Assessment Report (Bindoff et al., 2007), during the period 1993-2003, altimetry-based rate of sea level rise (of 3.1 +/- 0.4 mm/yr) can be explained by 1.6 +/- 0.25 mm/yr steric sea level and 1.2 +/- 0.2 mm/yr land ice contributions respectively (note that uncertainties quoted here correspond to the 95% errors range). Thus a new question is raised: could the recent rate of sea level rise (since 2003) be explained by fresh water input to the ocean alone as a result of enhanced land ice (and eventually land waters) contribution? In the present study, we try to answer this question by estimating the ocean mass change contribution to sea level using space gravimetry data from the GRACE mission launched in March 2002. GRACE provides spatio-temporal variations of the Earth gravity at monthly or less temporal resolution and ~300-400 km ground resolution (Tapley et al., 2004). Numerous studies published in the recent years have shown that GRACE can offer useful constraints on ocean mass change (e.g., Chambers et al., 2004; Lombard et al., 2007), on the mass balance of the ice sheets [e.g., Velicogna and Wahr, 2006a,b; Chen et al., 2006a,b; Lutchke et al., 2006; Ramillien et al., 2006) and on land water contribution to sea level (Ramillien et al., 2008). Here we analyse GRACE data over a 5.5 year time span (August 2002 through February 2008) over oceans, land and ice sheets to estimate the total fresh water mass contribution to past few years sea level rise. We discuss the total fresh water input to the oceans comparing ocean mass change and ice sheet contribution inferred from GRACE with recent independent estimates for the mass balances of the ice sheets and mountain glaciers. In addition as shown by Lombard et al.(2007), comparing the altimetry-derived global mean sea level change with GRACE-based ocean mass change provides an estimate of the steric (i.e., thermal expansion plus salinity effect) contribution to sea level. We also follow this approach here and compare altimetry/GRACE-based steric sea level with Argo-based estimate.

2. Ocean mass variation from GRACE

We have analysed geoid data from the GRACE space mission to estimate the change in mean mass of the oceans since mid-2002. We follow the same procedure as in Lombard et al. (2007), except that we use here the most recent geoid solutions (RL04 Level-2 products) released by the GeoForschungsZentrum –GFZ- (Flechtner, 2007). This data set covers the period August 2002 to February 2008 (~5.5 years). The geoid solutions consist of spherical harmonics coefficients up to degree and order 120 at monthly interval. To work with geoid anomalies, we remove from each monthly solution, a mean solution averaged over the whole 5.5-year time span. In the geoid solution determination process, an ocean model is removed. As the geoid solution over the oceans represents departure from the model, we add back the initial ocean model. To estimate the ocean mass component, we construct a geographical mask over the whole oceanic domain and compute, at each time step, the convolution product between spherical harmonics of mask and geoid anomalies. We limit the spherical harmonic expansion to degree 50 (corresponding to a ground resolution of ~400 km) to minimize the resonance effects affecting higher harmonic degrees [see Swenson and Wahr, 2006). We next express the results in terms of Equivalent Sea Level, noted ESL (see Lombard et al., 2007 for details about the GRACE data analysis).

The raw GRACE-based ocean mass time series is dominated by an annual cycle caused by the annual exchange of water between land and oceans (Cazenave et al., 2000). As we are interested here in the interannual fluctuations, we remove the annual cycle. The resulting time series, shown in Fig.1, has a slightly negative slope of ~ -0.12 +/- 0.06 mm/yr over the time span January 2003-December 2007 (we consider this time span –called 2003-2008- to work with an integer number of years). It is shown in Fig.1. However, a GIA correction has to be applied to this raw ocean mass time series. In effect, GIA causes a secular change in the mean oceanic geoid that needs to be removed from the GRACE-based raw ocean mass time series to obtain the real water mass change of the oceans. This linear correction is quite large and available from GIA modelling only. It varies from ~ 1. mm/yr to 2 mm/yr (in ESL unit), depending on modelling assumptions (Willis et al., 2008; Tamisiea et al., 2008; Peltier et al., 2008). Lombard et al. (2007) used a GIA correction of 1.7 mm/yr following Tamisiea et al. (2008). Willis et al. (2008) used a value closer to 1 mm/yr. Recently Peltier et al. (2008) reevaluated, under various modelling assumptions, the GIA corrections that need to be applied to satellite data (satellite altimetry and GRACE) when determining global mean sea level rise and ocean mass change. They show that Earth rotation effects have strong influence on the ocean mass GIA correction and recommend to use an ocean mass GIA correction of ~2 mm/yr that accounts for the rotational effects. Here we use this value. We will see below that such a value allows us to close the sea level budget. Corresponding GIA-corrected ocean mass time series (annual cycle removed plus 12-month smoothing) is shown in Fig. 1. We note that during the 2003-2008 period, the ocean mass has increased almost linearly, at a rate of 1.9 +/- 0.1 mm/yr . This increase results from fresh water mass input to the oceans as a result of land ice loss and eventually land waters.

3. Ice sheet contribution from GRACE

We now estimate the ice sheet contribution from GRACE over time span 2003-2008. Two methods are compared:

(1) We average the GRACE signal over the whole Earth surface and remove the ocean contribution using the ocean mask as explained in section 2. We also average the GRACE signal over the whole land surface using a land mask (excluding the ice sheets). The difference between the two averages provides an estimate of the ice sheet contribution.

(2) We average the GRACE signal using dedicated masks for Greenland and Antarctica as explained in Ramillien et al. (2006).

Although the two calculations are not independent, they provide an upper bound for the so-called leakage effect, i.e., the contamination from far field gravity signals not due to the ice sheets (at a given location, geoid height not only reflect local mass anomalies but also far field anomalies because of the inverse distance relationship between geoid and mass; such a contamination is amplified over small size regions like Greenland because of the low GRACE resolution, of ~ 400 km). We expect that method 1 minimizes the leakage effects.

Fig. 2 shows the ice sheet contribution expressed in equivalent sea level estimated by method 1. The raw time series exhibits a slightly positive trend of 0.4 +/- 0.1 mm/yr ESL. To this curve we need to add the GIA correction over the ice sheets (as over the oceans, GRACE cannot separate climate-related surface mass change from solid Earth mass change related to GIA). For Greenland, this correction is almost negligible [e.g., Ramillien et al., 2006). This is not the case however for Antarctica. In Ramillien et al. (2006), we used a GIA correction for Antarctica of 0.5 mm/yr ESL based on Ivins and James (2005) model. Such a value is also that preferred by Barletta et al. (2007) who investigated a large range of upper and lower mantle viscosities to estimate the GIA correction to be applied to GRACE-derived ice sheet mass balance. We use this value here to compute the GIA-corrected time series shown in Fig.2. The resulting trend amounts to 1.0 +/- 0.1 mm/yr ESL. It represents the total ice sheet contribution to sea level as estimated from GRACE over the 2003-2008 time span. In terms of ice mass loss, this corresponds to ~ 360 +/- 36 Gigatons/year.

Results from method 2 are shown in Fig.3a and 3b (Greenland and Antarctica contributions expressed in ESL). For Antarctica, we have applied a GIA correction of 0.5 mm/yr (ESL) as discussed above. In both figures, we compared the GFZ GRACE-based time series with another estimate based on another GRACE product (i.e., from the Groupe de Recherche en Geodesie spatiale –GRGS- group, Biancale et al., 2006), to check the consistency of the estimated trend. For each ice sheet, the two sources of data lead to very similar trends (with differences smaller than 0.02 mm/yr). Taking the mean value from the two data sources, we obtain a GRACE-based Greenland contribution to sea level of 0.38 +/- 0.05 mm/yr (i.e., -136 +/- 18 Gigatons/year ice mass loss) over 2003-2008. The Antarctica contribution (GIA correction applied) is 0.56 +/- 0.06 mm/yr ESL over the same period (i.e., -198 +/- 22 Gigatons/year ice mass loss). Summing the two ice sheet contributions leads to 0.95 +/- 0.08 mm/yr ESL over 2003-2008, in good agreement with the result of method 1. The small difference between the two methods places an upper bound on the leakage effects.

4. Total land ice contribution to sea level

Ice sheets

Several estimates of the ice sheet mass balance from GRACE have been published in the recent years (Velicogna and Wahr, 2006a,b; Chen et al., 2006a,b; Ramillien et al., 2006). Significant uncertainty in trends can be noticed between these different published results. Early results were based on rather short time series. Hence lengthening the time series may lead to different results because of seasonal and interannual variability. As discussed in Cazenave (2006), another cause of discrepancy arises from differences in data processing and methodology developed by the various GRACE project groups when computing the geoid solutions. From most recent published results, including those of the present study, we note that GRACE products from GFZ, GRGS and the 'Mascons' approach (the regional method developed by Lutchke et al., 2006) provide rather converging results, at least for Greenland (see also Forsberg, 2008), with current rates of ice mass loss of ~ 130-150 Gigatons/year. Higher rates are found by Velicogna and Wahr (2006a) (210 Gigatons/year for Greenland; e.g., Witze, 2008) and Chen et al. (2006a) based on Center for Space Research –CSR- geoids. So far, the reason for this discrepancy remains unclear.

From a compilation of published results based on different remote sensing techniques and modelling, Meier et al. (2007) reported for year 2006 contributions (in ESL) of 0.5 +/- 0.1 mm/yr, 0.32 +/- 0.04 mm/yr and -0.15 +/- 0.07 mm/yr for Greenland, West Antarctica and East Antarctica respectively, leading to a total ice sheet contribution of ~0.7 +/- 0.15 mm/yr for that particular year. Recently Rignot et al. (2008) reassessed Antarctic ice mass balance using radar interferometry and surface mass balance modelling. They conclude that East Antarctica has remained almost in balance since 1992 while accelerated ice mass loss is reported in West Antarctica. The net Antarctica contribution for year 2006 amounts to 0.54 +/- 0.2 mm/yr. This is three times Meier et al.'s value of 0.17 mm/yr, mainly a result of positive mass balance for East Antarctica in the latter study. It is worth to note that our GRACE-based estimate for Antarctica over the past 5 years is in good agreement with Rignot et al. (2008) estimate. These results suggest that recent years ice sheet contribution to sea level has increased compared to the 1990s (Lemke et al., 2007). In the following we consider for the total ice sheet contribution, the average of the two methods presented in section 2, i.e., ~1.0 +/- 0.15 mm/yr for 2003-2008.

Glaciers and ice caps

Between 1990 and 2003, the IPCC 4th Assessment Report determined a Glacier and Ice Cap (GIC) contribution to sea level rise of 0.77 +/- 0.22 mm/yr (Lemke et al., 2007). There are still very few updated estimates of GIC losses for the most recent years (beyond 2003) due to the difficulty to gather mass balance measurements performed worldwide by different research groups. Kaser et al. (2006) reported a contribution to sea level rise of 0.98 +/- 0.19 mm/yr for 2001-2004, slightly larger than during the previous decade. Using the same data as Kaser et al. (2006) and assuming that ice losses by GIC increased linearly with time since year 2000, Meier et al. (2007) found the GIC contribution to be 1.1 +/- 0.24 mm/yr ESL for year 2006.

The enhanced mass losses from GIC proposed by Meier et al. (2007) is supported by recent evidences of accelerated ice thinning rates in Alaska (Chen et al., 2006c), Svalbard (Kohler et al., 2007) and in Himalaya (Berthier et al., 2007). The acceleration is also clearly demonstrated by the updated (although not yet complete) glacier mass balance measurements collected by the World Glacier Monitoring Service (WGMS, available at http://www.geo.unizh.ch/wgms/). Analysis of a subset of thirty reference glaciers spread in nine mountain ranges shows that the three years with the strongest ice losses appear after 2002. The mean mass balance for 2002-2006 (the last four hydrological years available) is two to three times more negative than during the previous 10 years. In the following we consider the value of 1.1 +/- 0.24 mm/yr ESL from Meier et al. (2007) as representative of the 2003-2008 time span and use it for the sea level budget.

5. Total mass contribution to the sea level budget over 2003-2008

Summing the ice sheet and glacier contributions as discussed above, leads to a total land ice component of 2.1 +/- 0.25 mm/yr ESL over 2003-2008. To this value should eventually be added a small contribution from land waters. In a previous study (Ramillien et al., 2008), we estimated to ~ 0.17 +/- 0.1 mm/yr, the land water contribution to sea level using GRACE data (GFZ geoids, release RL03) over 2003-2006. An updated estimate based on GFZ RL04 GFZ and GRGS GRACE data leads to about the same value over 2003-2008. In the following we use the Ramillien et al. (2008).

Comparing the GRACE-based ocean mass trend (1.9 +/- 0.1 mm/yr; see section 2) with the total land ice plus land waters contribution estimated independently (2.2 +/- 0.28 mm/yr; sections 3 and 4) gives satisfactory agreement for a GIA correction of 2 mm/yr. In a way this provides constraints on the GIA correction, suggesting that the upper range of proposed values is indeed indicated. As mentioned above, this upper range is recommended by Peltier et al. (2008) because of Earth rotation effects. The comparison also provides constraints on glacier melting contribution, since with GRACE, we can compute separately ocean mass increase (sum of ice sheet mass loss and land waters) and ice sheet mass balance. Comparing the two provides constraint on glaciers melting. We note that the latter contribution agrees well with published results based on *in situ* observations and remote sensing.

Fig.4 compares for the 2003-2008 period, the observed (from T/P and Jason-1 altimetry) sea level curve (from Ablain et al., 2008) to GRACE-based ocean mass change (with a GIA correction of 2 mm/yr) and total land ice plus land waters contribution discussed above. We note that land ice plus land waters has contributed for 75%-85% to recent sea level rise, i.e., significantly more than during the decade 1993-2003 (Bindoff et al., 2007).

6 . Steric sea level inferred from altimetry and GRACE and computed with Argo

As shown in Lombard et al. (2007), it is possible to estimate the steric sea level from the difference between the altimetric (i.e., total) sea level and the GRACE-based ocean mass component. Corresponding steric sea level curve for 2003-2008 is presented in Fig.5 (assuming a GIA correction of 2 mm/yr for the ocean mass estimate). The steric sea level increased on average since early 2003 through 2006, then shows a slightly decreasing trend. The latter behaviour results from the fact that altimetric sea level flattens since 2006 while the ocean mass continues to increase. If this steric sea level behaviour is real, it could be related to the particularly strong recent La Nina cold phase (Kennedy, 2007). The average slope of the steric sea level curve over 2003-2008 is small, on the order of 0.31 +/- 0.15 mm/yr. In Fig.5 is also presented the steric sea level computed from the difference between satellite altimetry and total land ice (i.e., ice sheet contribution estimated in this study plus glacier contribution from Meier et al., 2007) plus land waters curve. It is interesting to note that it closely follows the altimetry minus ocean mass curve. Its trend is also similar.

We now provide an independent estimate of the steric sea level using temperature and salinity data from Argo profiling floats. When available, delayed-mode data are preferred to real-time ones (i.e. for half of the floats) and only measurements with Argo quality control flags at '1' are used. As real-time quality controlled checks applied on the Argo data set are very simple and automated, additional quality controls were first performed following the method described in Guinehut et al. (2008). It compares collocated sea level anomalies from altimeter measurements with steric height anomalies calculated from the Argo temperature and salinity profiles. By exploiting the correlation that exists between the two data sets (Guinehut et al., 2006), along with mean representative statistical differences between the two, the altimeter measurements are used to extract random or systematic errors in the Argo float time series (drift, bias, spikes, etc). About 4% of the floats were deleted by this method.

Steric heights at the surface are then computed relative to the 900-m depth from Argo temperature and salinity profiles. The 900-m depth was chosen as a compromise between data coverage and maximum sampled depth to provide optimum spatial and temporal coverage. Steric changes below 900-m do contribute to the sea level budget on multi-decadal time scales but observations and models suggest that major contributions come from the upper ocean [e.g., Antonov et al., 2005, Wunsch et al., 2007].

Argo floats profiles being discrete measurements in time and in space, steric sea level grids at 1/3° resolution are constructed at monthly interval. Mapping is based on an optimal interpolation method (Bretherton et al., 1976), using a temporal correlation scale of 45 days and a spatial correlation scale that varies with latitude, from 1500 km at the equator to 700 km at 50°N (larger values are used in the zonal direction than in the meridional one). In order to take into account errors associated with mesoscale variability aliasing, noise-to-signal ratio is fixed to 2.0 for each in-situ measurement. Besides, a contemporaneous Argo climatology representing the time-mean is removed from the individual steric height prior to mapping. Finally, monthly steric height anomaly grids are globally averaged to produce steric sea level time series.

In order to precisely quantify the impact of Argo data sampling and methodology used to calculate the globally averaged values, the AVISO multi-mission combined sea level products (Ducet et al.,

2000) are interpolated at the time and location of each Argo float profile. Sea level maps are then reconstructed using the same mapping technique as for steric maps. This allows us to estimate the impact of the variable Argo coverage. At the beginning of 2002, Argo sampling covers about 40 % of the ocean. It reaches around 70 % in 2003, then 80 % at the beginning of the year 2004. After mid-2006, more than 90 % of oceanic areas are sampled. Here we consider Argo data over 2004-2007 only because of the still poor 2003 coverage. The globally averaged steric sea level computed from the gridded data is finally compared altimetry-based sea level (SSALTO/DUACS multi-mission combined products, Ducet et al., 2000). The two curves compare very well over 2004-2008 with a 2.4 mm rms difference, the trend being only slightly reduced by 0.02 mm/year. Fig 5 presents the Argo-based steric sea level curve (seasonal cycle removed; as for ocean mass variations, the steric sea level curve for the upper 900-m depth is dominated by an annual cycle due to seasonal heating and cooling of the upper ocean). The curve is rather flat over the 2004-2008 time span. Corresponding linear trend is small and on the order of 0.37 +/- 0.1 mm/year. Even if the year to year variability does not match exactly the altimetry/GRACE steric sea level curve (possibly a result of the data processing and deep ocean contribution), it is remarkable to obtain such an agreement. These two independent estimates of steric sea level trend presented in this study are slightly higher than Argo-based values from Willis et al. (2008). Nevertheless, these results strongly indicate a pause in the rate of steric sea level rise in the past few years. The independent estimate based on GRACE and satellite altimetry data indicate that it is not due to any Argo instrumental problem.

7. Conclusion

From the results presented in this study, we see that confronting independent estimates of ocean and land contributions to sea level with altimetry results leads to a rather coherent picture for recent years variations. This can be summarized as follows: since 2003, sea level has continued to rise but with a rate (of 2.5 +/- 0.4 mm/yr) somewhat reduced compared to the 1993-2003 decade (3.1 +/- 0.4 mm/yr). Over 2003-2008, the GRACE-based ocean mass has increased at an average rate of ~1.9 mm/yr (if we take the upper range of possible GIA corrections as recommended by Peltier et al., 2008). Such a rate agrees well with the sum of land ice plus land water contributions (i.e., GRACE-based ice sheet mass balance estimated in this study, GRACE-based land waters plus recently published estimates for the current glacier contribution). These results in turn offer constraints on the ocean mass GIA correction, as well as on the glacier melting contribution.

The steric sea level estimated from the difference between altimetric (total) sea level and ocean mass displays increase over 2003-2006 and decrease since 2006. On average over the 5 year period (2003-2008), the steric contribution has been small (on the order of 0.3 +/- 0.15 mm/yr), confirming recent Argo results (this study and Willis et al., 2008).

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Table 1: Sea level rise and the different contributions over 2003-2008 (numbers are from the present study, except for glaciers and ice caps)

Data source	**Rate (mm/yr)**
Sea Level (altimetry) 2003-2008	2.5 +/- 0.4
Ocean mass (GRACE) 2003-2008	1.9 +/- 0.1
Ice sheets (GRACE) 2003-2008	1. +/- 0.15
Glaciers and Ice Caps 2003-2008 Meier et al. (2007)	1.1 +/- 0.24
Terrestrial Waters 2003-2008	0.17 +/- 0.1
Sum of ice and waters	2.2 +/- 0.28
Steric sea level (altimetry minus GRACE) 2003-2008	0.31 +/- 0.15
Steric sea level (Argo) 2004-2008	0.37 +/- 0.1

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Figure Captions

Fig.1: Ocean mass change from GRACE over 2003-2008. The open circled curve is the raw time series. The black triangles curve corresponds to the GIA corrected time series.

Fig.2: Total ice sheet contribution to sea level estimated from GRACE over 2003-2008 (method 1; see text). The lower curve (crossed solid line) corresponds to raw data. The upper curve (dotted line with crosses) is the GIA corrected curve.

Fig.3: (a) GRACE-based contribution of Greenland ice loss to sea level (2003-2008). The curve with open circles corresponds to GFZ geoids. The curve with black squares corresponds to GRGS geoids.

(b) Same as (a) but for Antarctica. A GIA correction of 0.5 mm/yr ESL has been applied.

Fig.4: Upper curve (crossed line) : altimetry-based sea level curve; Middle curve (open circles) : total land ice contribution using the GRACE-based ice sheet mass balance (this study) and Meier et al. (2007) glaciers contribution; Lower curve (black triangles) : GRACE-based ocean mass change (GIA correction applied).

Fig.5: Steric sea level. Upper curve (black triangles): estimated from the difference between altimetry and GRACE-based ocean mass. Middle curve (open circles) : estimated from the difference between satellite altimetry and total land ice plus land waters contribution; Lower curve : ARGO-based estimate (this study).

Fig.1

Fig.2

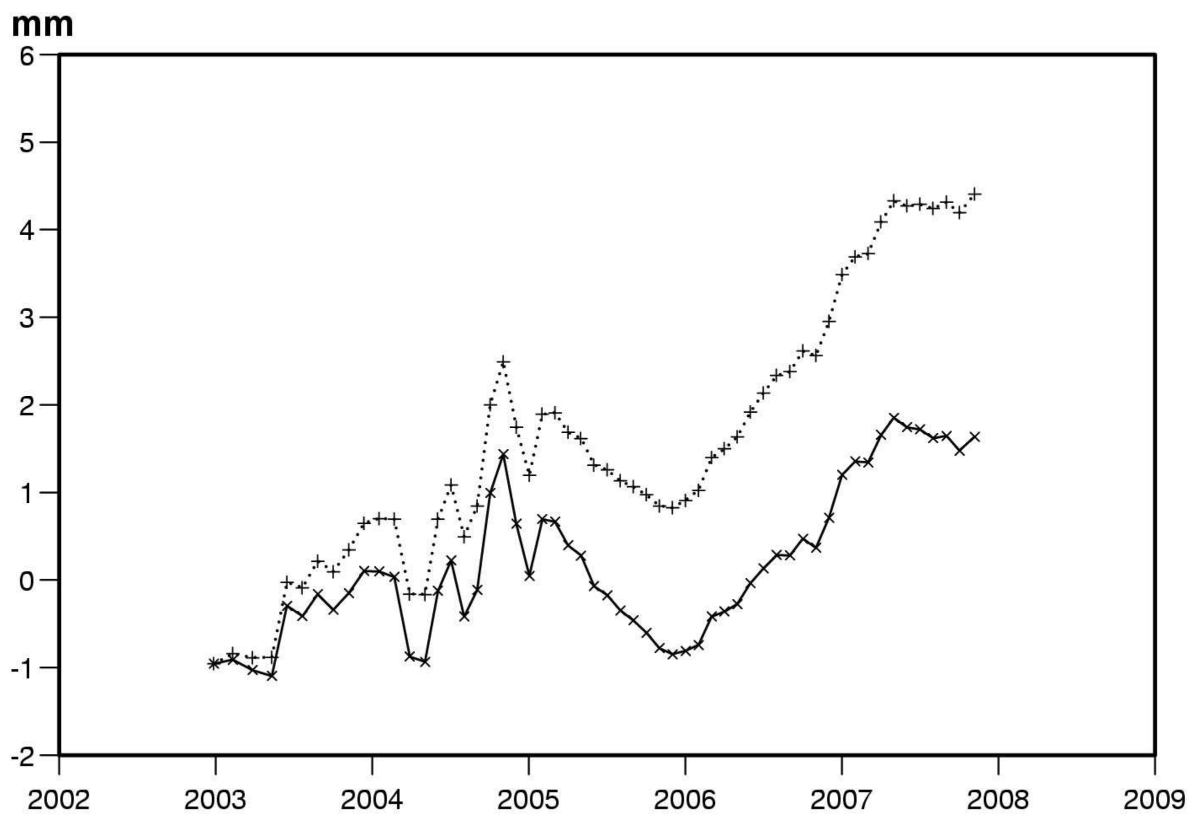


Fig.3a

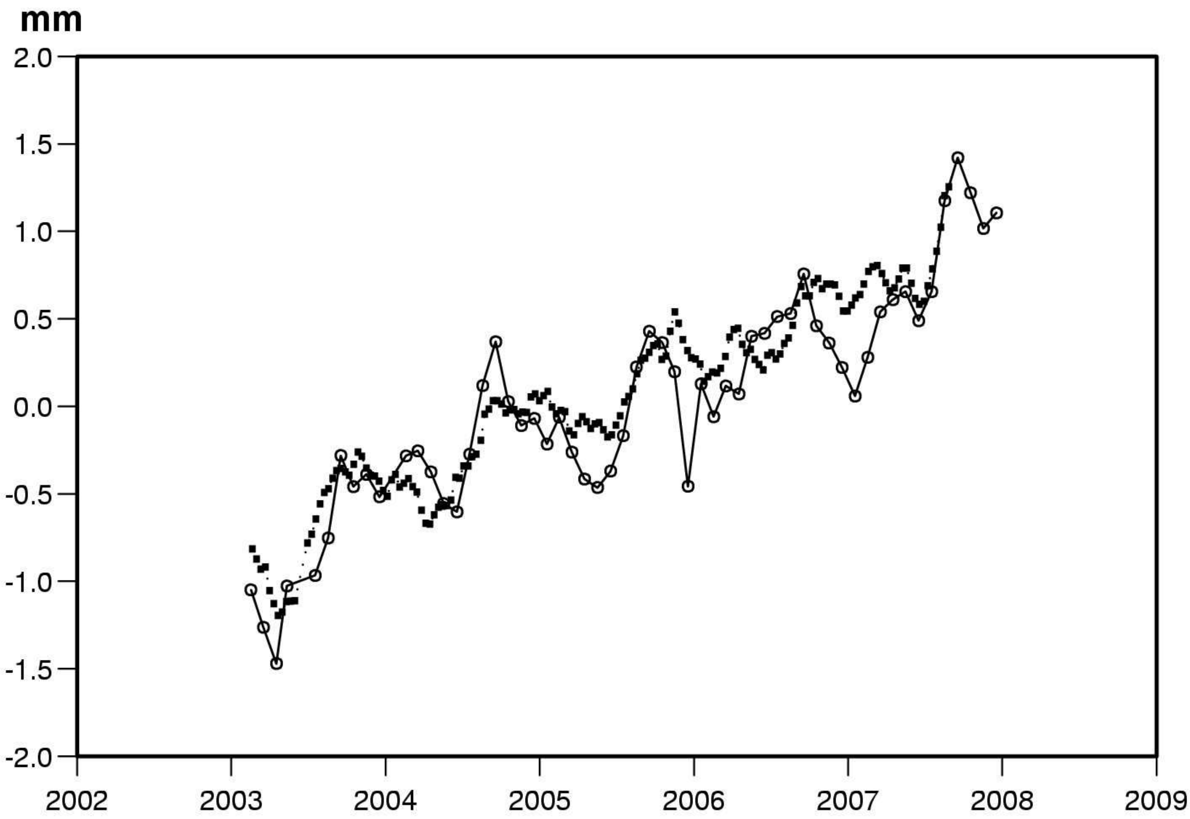
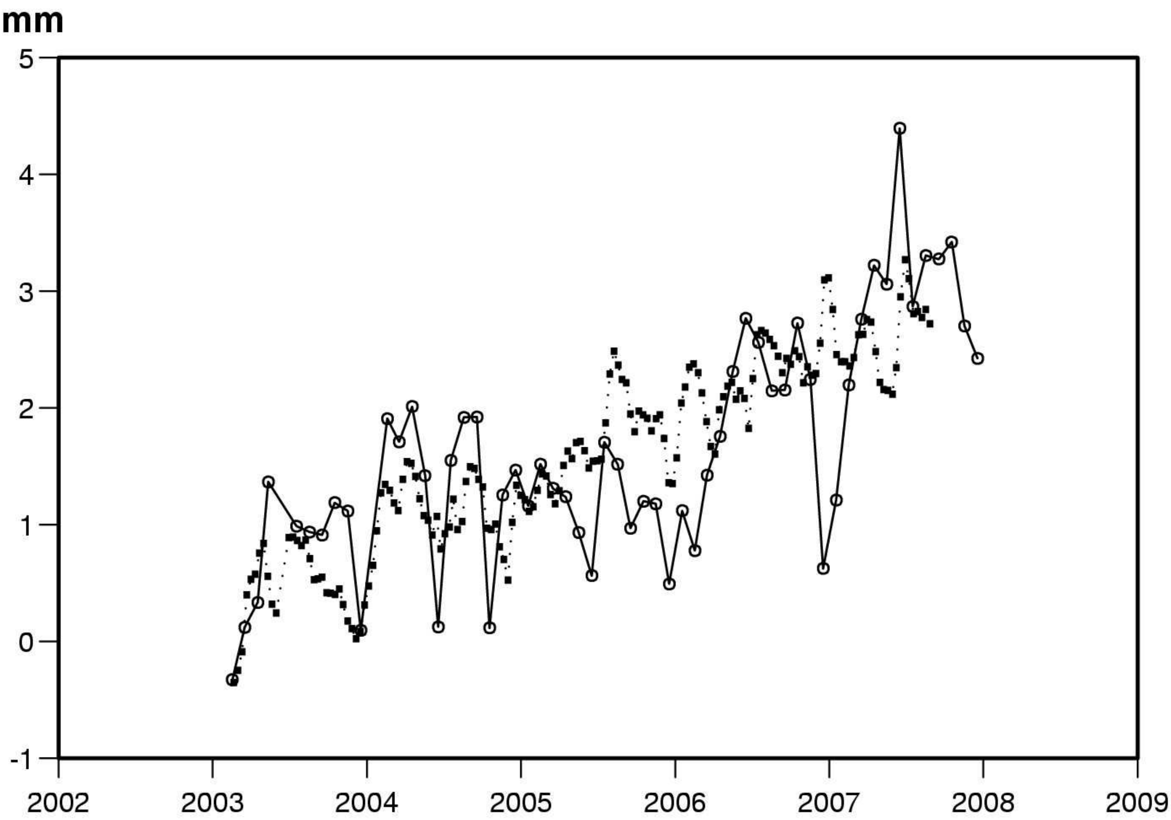

mm
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
2002
2003
2004
2005
2006
2007
2008
2009

Fig.3b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3
2
1
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-1
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2003
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2007
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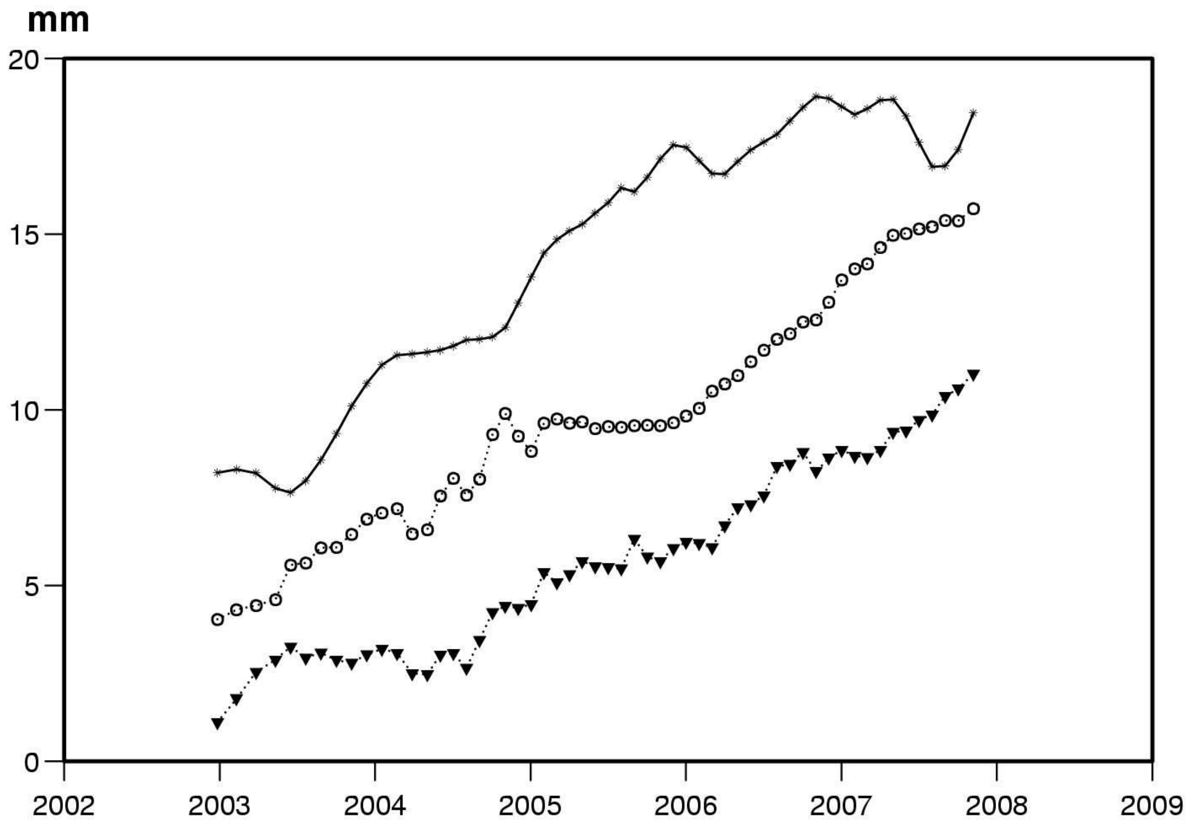
Fig.4


mm
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5
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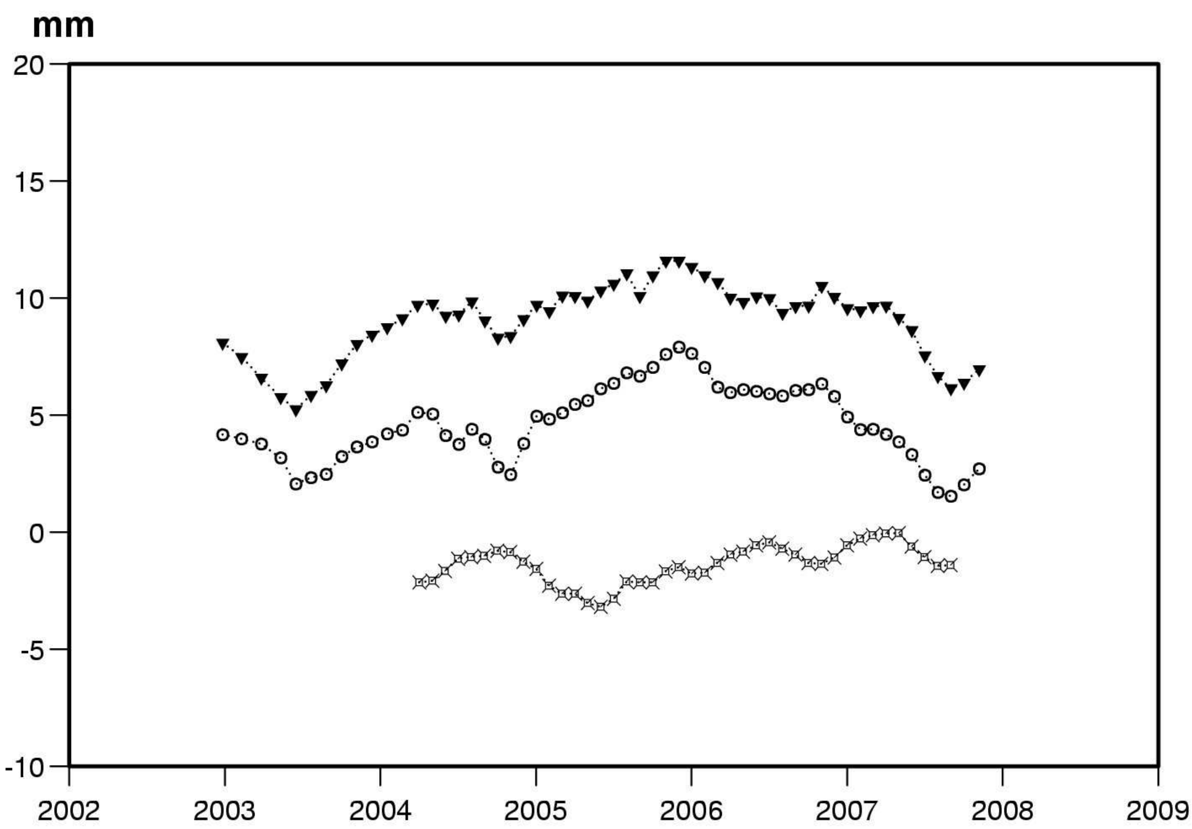
2009

Fig.5


mm
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2009